

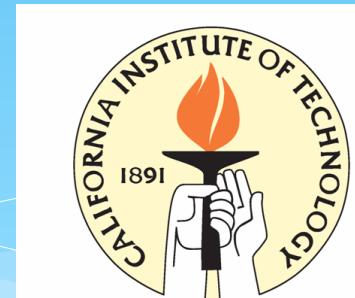
Error Analysis of Upper Tropospheric Water Vapor in CMIP5 Model using “A-Train” Satellite Observations and Reanalysis Data

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Background: Why UTWV is important?

- ❖ A recent study using “A-Train” satellite data confirms **a clear upper tropospheric amplification in humidity in response to increasing tropical SST during ENSO** (Takahashi et al., 2013).
- ❖ Existing climate models have predicted that the **rate of increase of UTWV under global warming is larger than that of water vapor in the lower troposphere** (Tett et al., 1996; Held and Soden, 2000; Soden et al., 2005; Minshwaner and Dessler, 2004)
- ❖ The radiative effect due to water vapor absorption is roughly proportional to the logarithm of its concentration at a given altitude, and **the strength of the feedback mechanism is regulated by the fractional change of water vapor, rather than the absolute change** (Soden et al., 2005; Soden et al., 2008).
- ❖ **The water vapor feedback is particularly sensitive to UTWV.**

Background: How well do models simulate UTWV?

Jiang et al. (2012), JGR

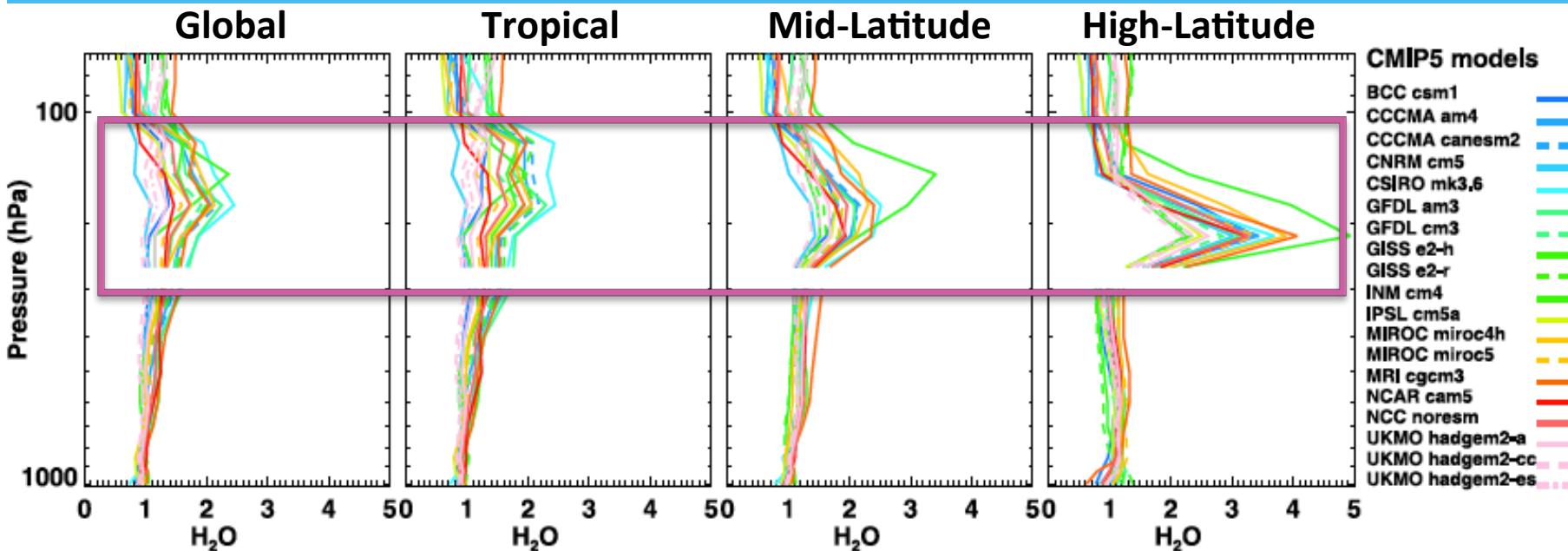
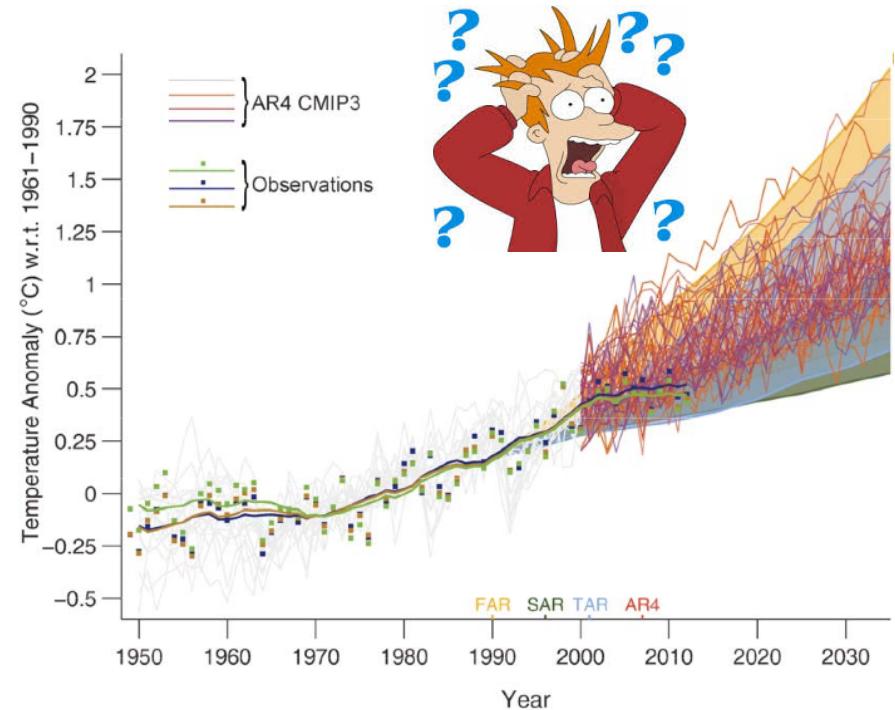


Figure 7. Ratio of multiyear CMIP5 modeled H₂O to A-Train observed values as a function of height.

- ❖ UTWV is one of the most **poorly** simulated quantities in climate models.
- ❖ The model spreads and their differences from the observations are larger in the UT than in the LT/MT.

Motivation: Improving the UTWV in climate models is important!!!

- ❖ Improving the UTWV in climate models is one of the essential tasks for reducing uncertainties of climate model simulations and projections.
- ❖ The dynamic and thermodynamic components control the water vapor anomalies uniquely at different levels under the various climates (Takahashi et al., 2013).
- ❖ However, the relative role of thermodynamics and dynamics in affecting the model errors of UTWV is unclear.



We aim to elucidate the thermodynamic (i.e., temperature) and dynamic (i.e., large-scale circulation + sub-grid clouds) sources of model errors in UTWV at different time scales: **climatological mean, seasonal cycle, and interannual variability.**



Data: satellite observation and model simulation

UTWV (215hPa) & LSWV (100hPa): The Microwave Limb Sounder on Aura

- The uncertainty in MLS H₂O is 20% at 215 hPa. Vertical resolution: ~2.5 km at 316-215 hPa. Horizontal resolution is 2.5° (longitude) × 2° (latitude).

MTWV (500hPa) & LTWV (850hPa) & Temperature:

Atmospheric Infrared Sounder on Aqua

- 13.5 km at horizontal at nadir with 1 km vertical resolution. The spatial resolution is 50 km, but aggregated on 1°×1° (longitude × latitude) grids.

Vertical pressure velocity (ω): European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-interim reanalysis

- Use as a proxy of large-scale circulation.

23 climate models: CMIP5/AMIP5

- Atmospheric global circulation models that use same observed SST, sea ice fractions, CO₂ concentrations and other external forcings as defined in the Atmospheric Model Inter-comparison Project (AMIP) framework.

Data period: Aug 2004- Dec 2008

- It is the overlapping period among MLS, AIRS, ECMWF, and CMIP5/AMIP.

Errors in Climatological Mean: UTWV Error Decomposition

$$q = RH \cdot q^*(T)$$

To test relative importance of thermodynamic and dynamic components of UTWV errors, we decompose UTWV errors as:

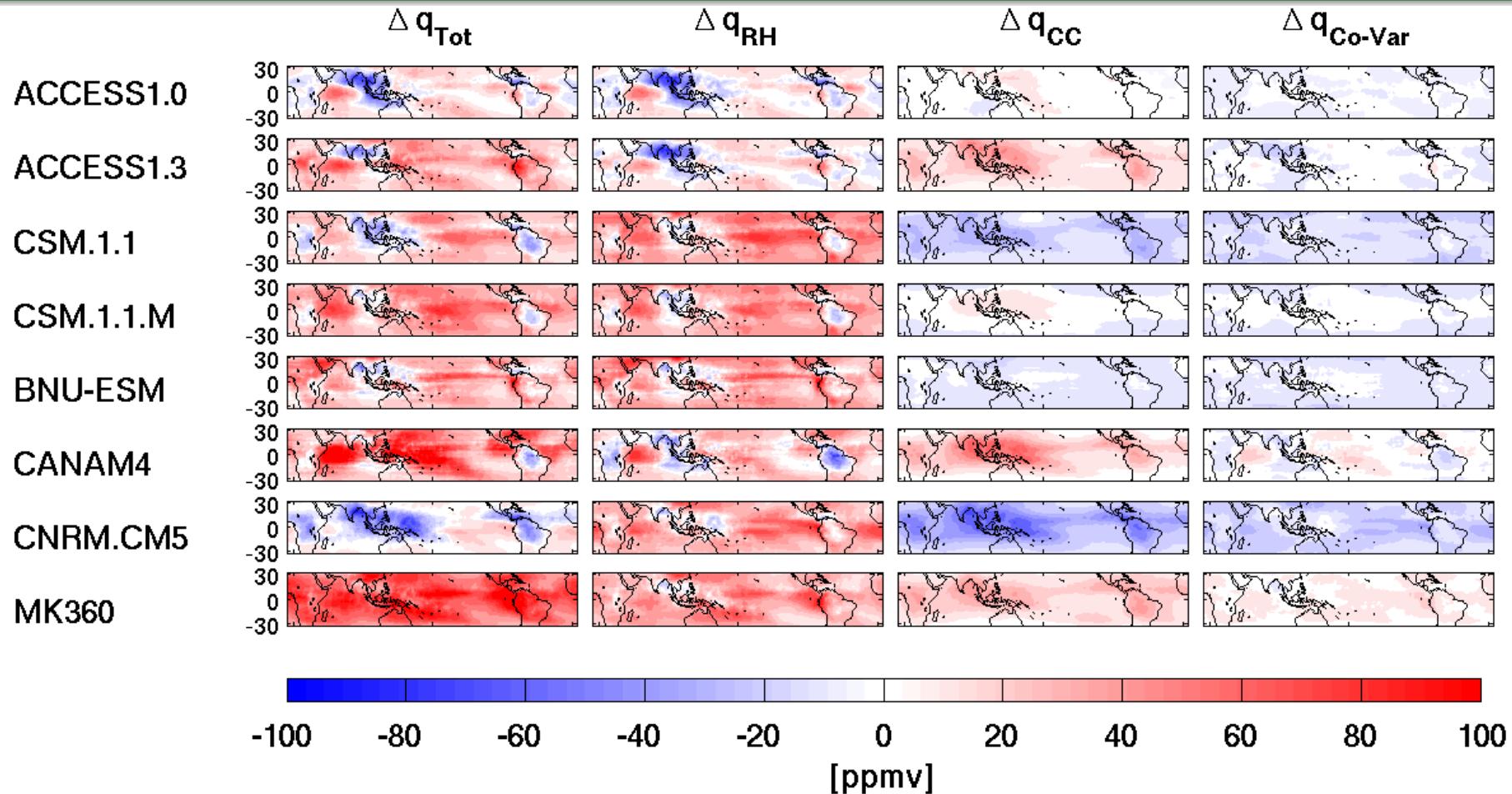
$$\Delta(*) = (*)_m - (*)_o$$

$$\Delta q_{Tot} = \underline{\Delta RH \cdot q^*(T)_o} + \underline{RH_o \cdot \Delta q^*(T)} + \underline{\Delta RH \cdot \Delta q^*(T)}$$

$$\Delta q_{Tot} = \Delta q_{RH} + \Delta q_{CC} + \Delta q_{Co-Var}$$

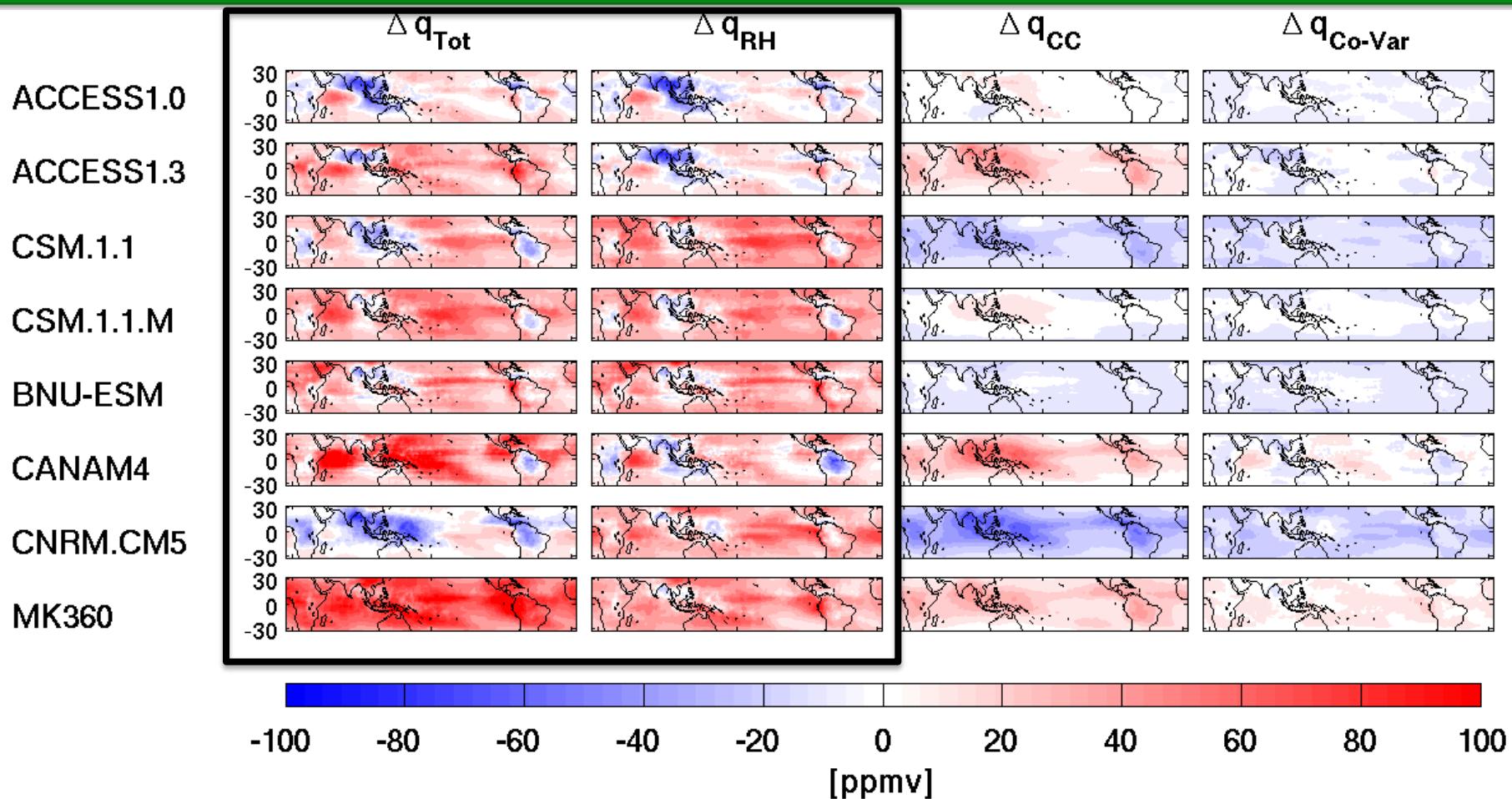
- ❖ Error due to RH is called Δq_{RH} , which is highly correlated with the circulation errors (spatial correlation ~ 0.5)
➔ dynamic component (large-scale circulation + sub-grid clouds)
- ❖ Error due to $q^*(T)$ is called Δq_{CC} because it is due to temperature error (Clausius-Clapeyron relationship)
➔ thermodynamic component

Errors in Climatological Mean: UTWV Error Decomposition



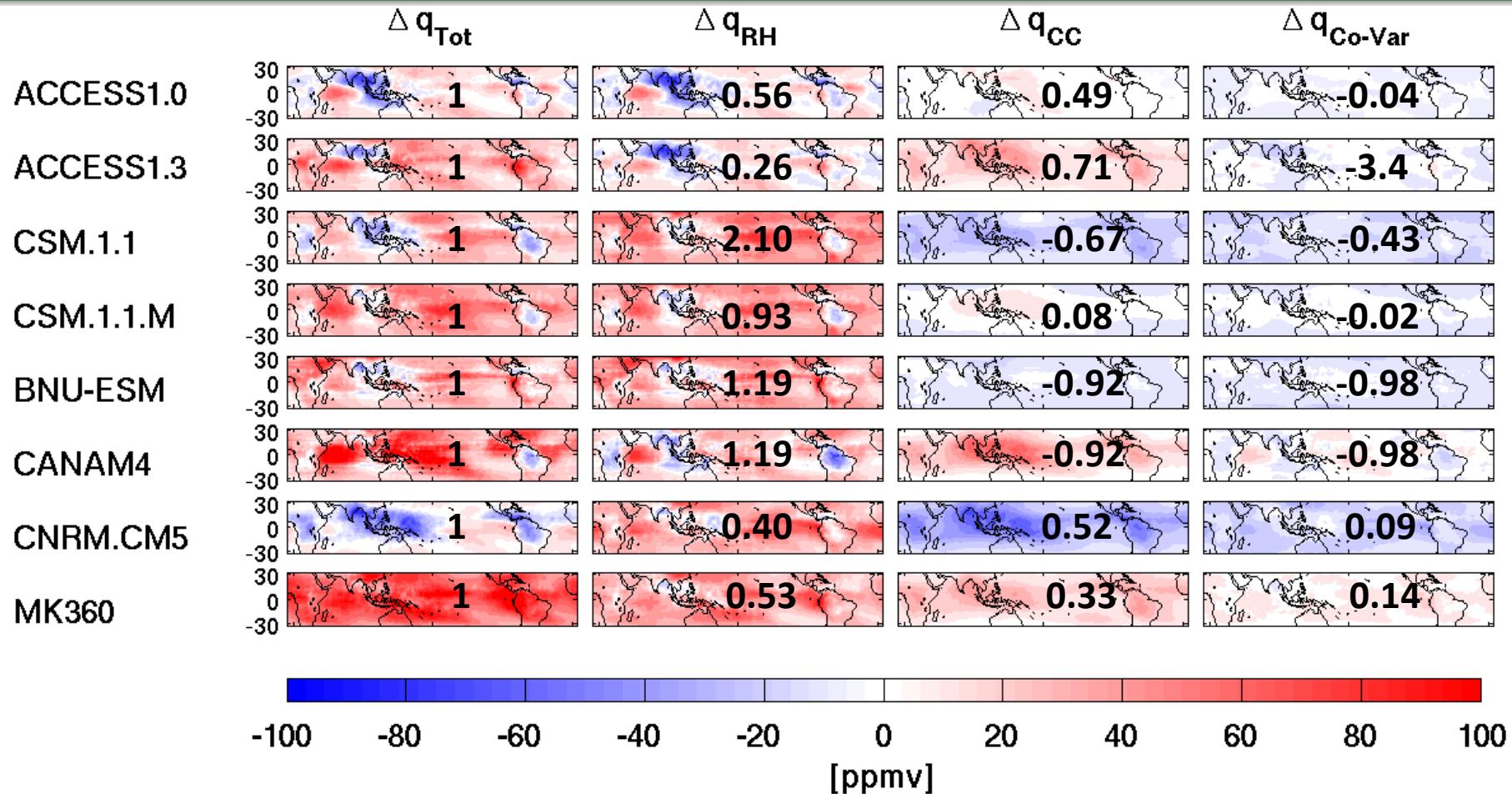
- ❖ Models generally have wet biases in the UT, except CNRM.CM5.
- ❖ Over the continental regions, models tend to have dry biases.

Errors in Climatological Mean: UTWV Error Decomposition



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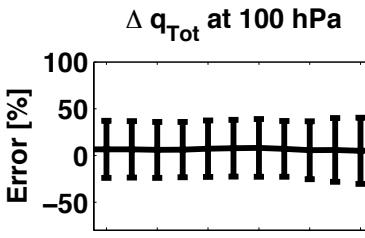
Errors in Climatological Mean: UTWV Error Decomposition



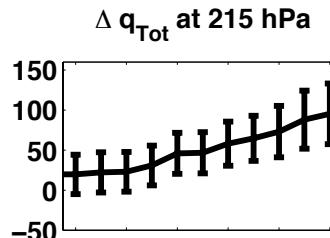
- ❖ Models generally have wet biases in the UT, except CNRM.CM5.
- ❖ Over the continental regions, models tend to have dry biases.
- ❖ 18 models show that the amplitudes of Δq_{RH} account for the largest proportion of Δq_{Tot}

Errors in Climatological Mean: Fractional UTWV Error Decomposition

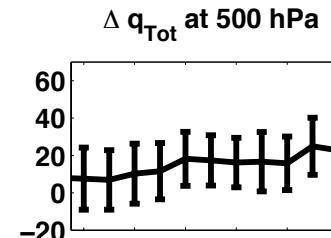
LS



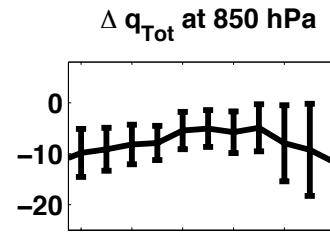
UT



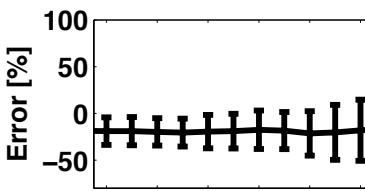
MT



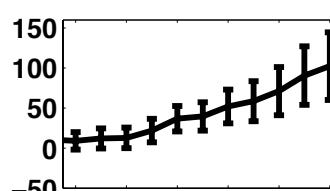
LT



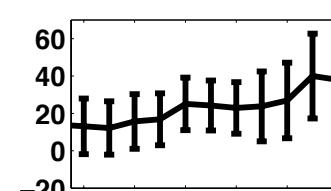
Δq_{RH}



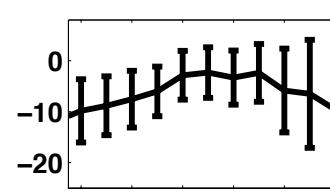
Δq_{RH}



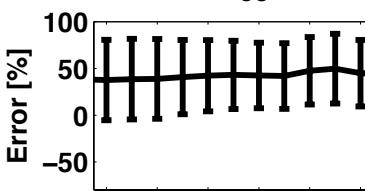
Δq_{RH}



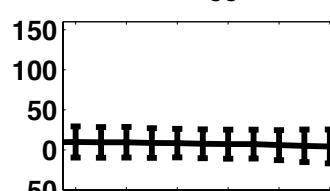
Δq_{RH}



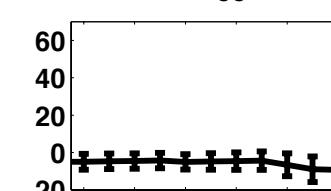
Δq_{CC}



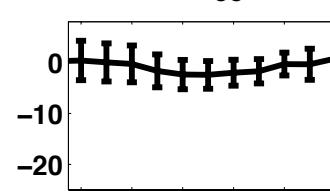
Δq_{CC}



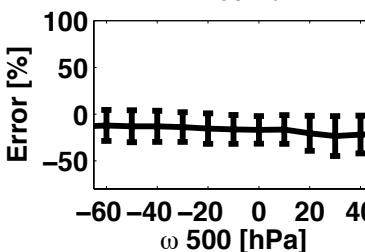
Δq_{CC}



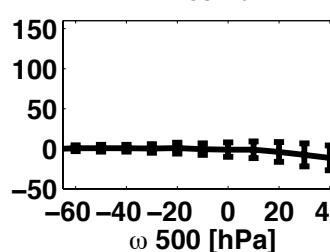
Δq_{CC}



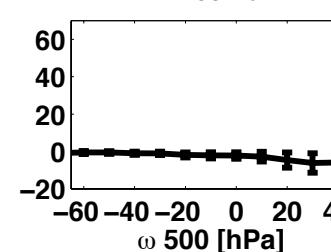
$\Delta q_{\text{Co-Var}}$



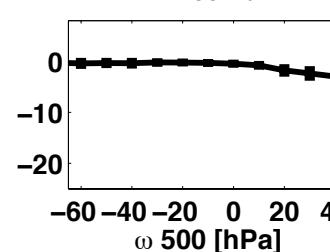
$\Delta q_{\text{Co-Var}}$



$\Delta q_{\text{Co-Var}}$

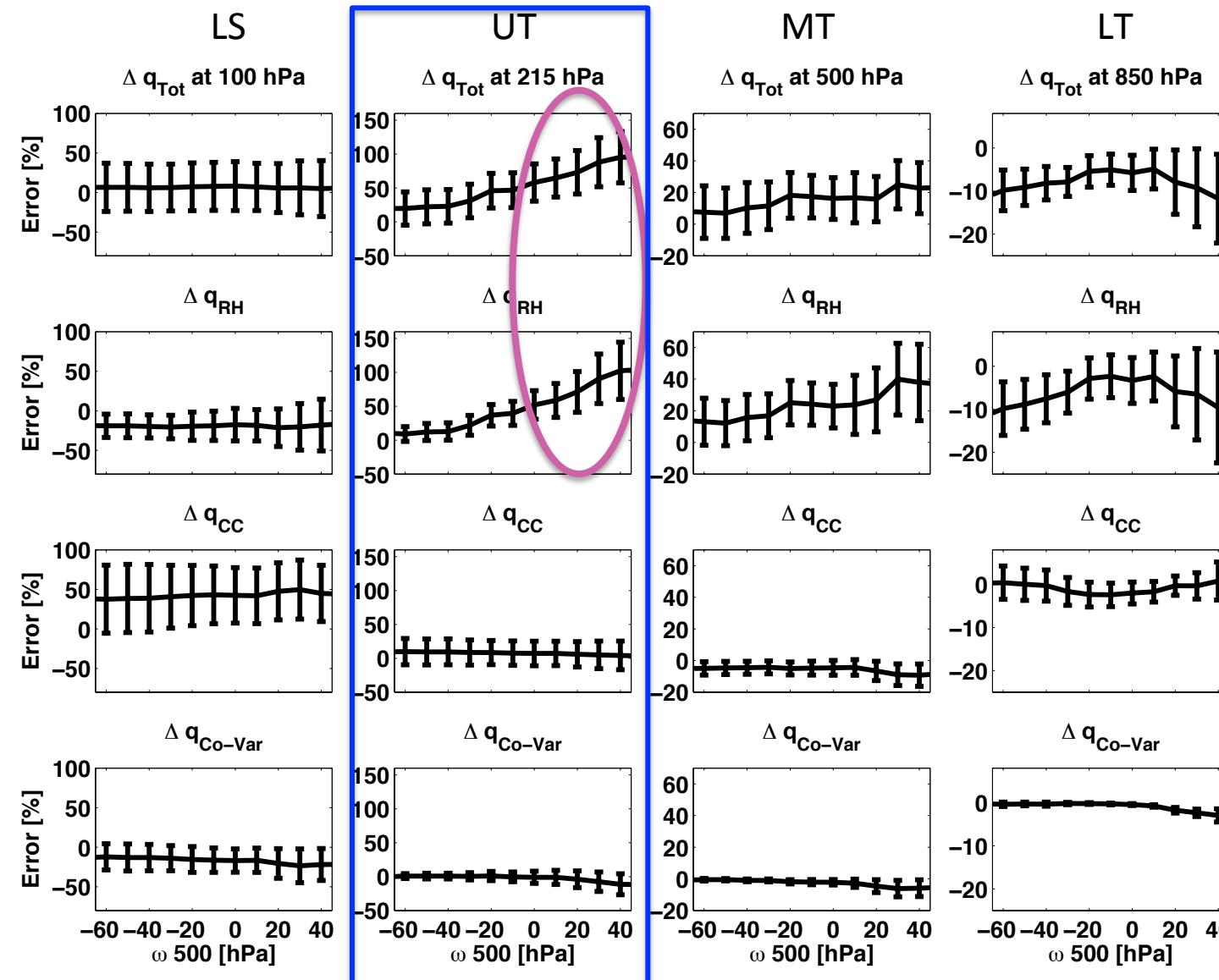


$\Delta q_{\text{Co-Var}}$



Each component is sorted by observed climatological ω_{500} with a bin interval of 10 hPa/day.

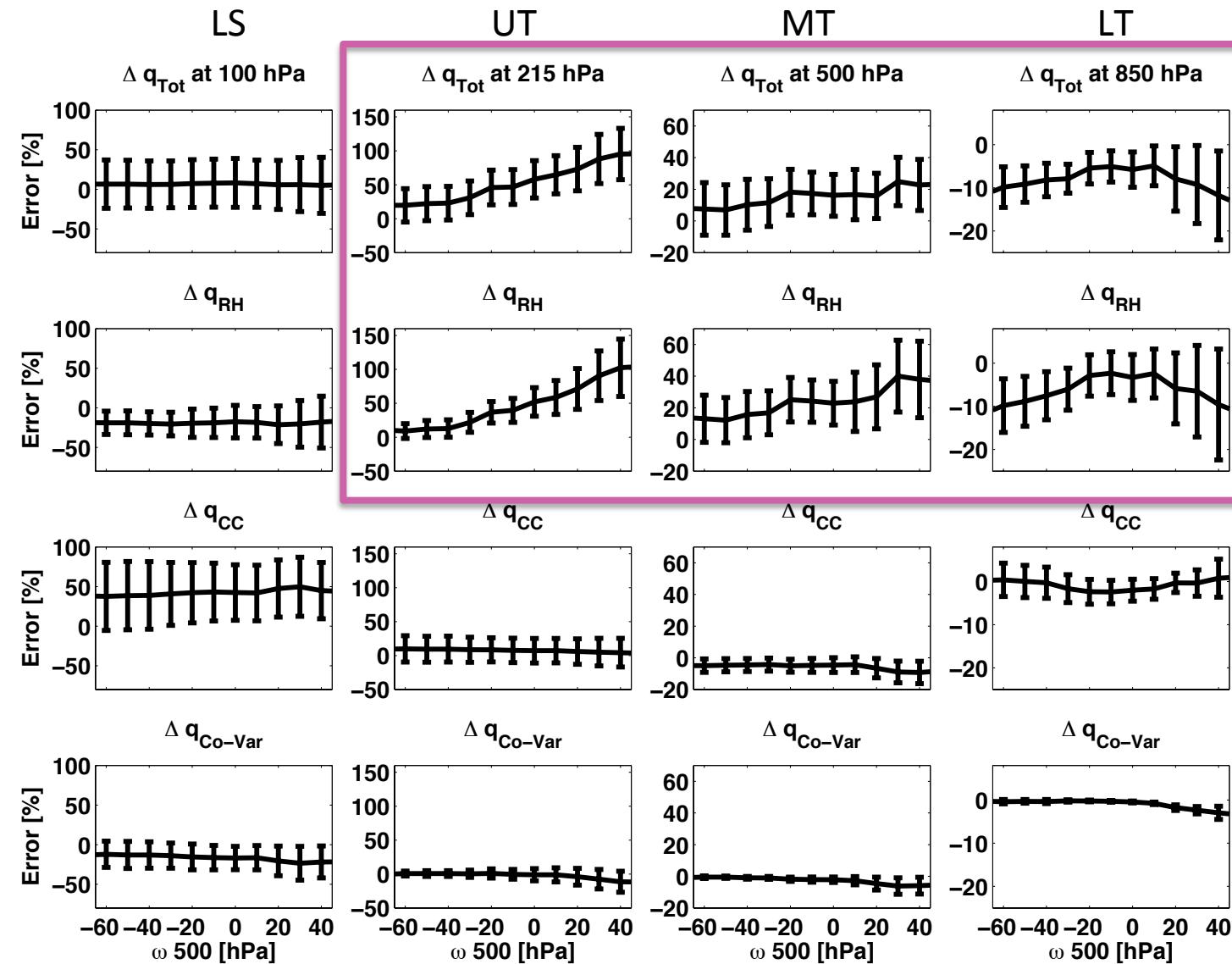
Errors in Climatological Mean: Fractional UTWV Error Decomposition



Each component is sorted by observed climatological ω_{500} with a bin interval of 10 hPa/day.

- ❖ The large positive errors are concentrated over the descending regimes.
- ❖ Consistent with previous result: simulated ω_{500} tends to have a negative bias in descending regimes (Su et al., 2013).

Errors in Climatological Mean: Fractional UTWV Error Decomposition



Each component is sorted by observed climatological ω_{500} with a bin interval of 10 hPa/day.

- ❖ **Dynamics play a dominant role** in the water vapor errors, except LS.

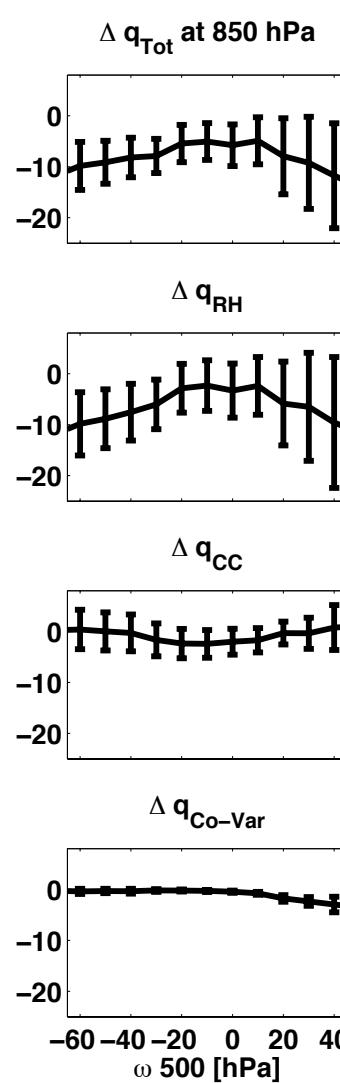
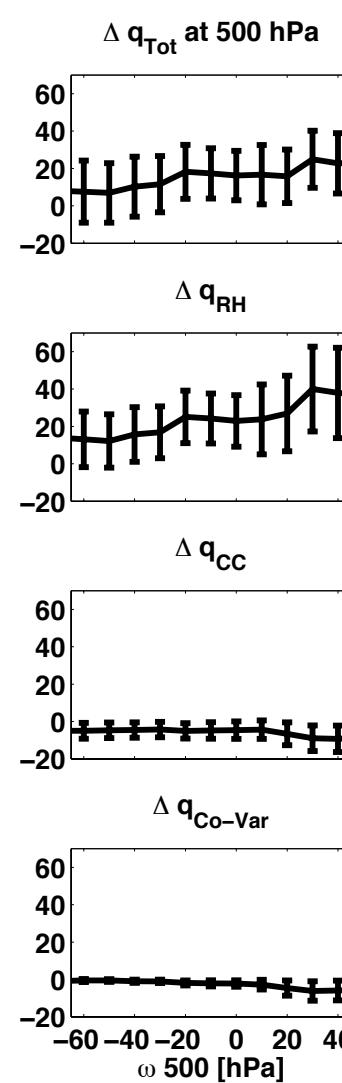
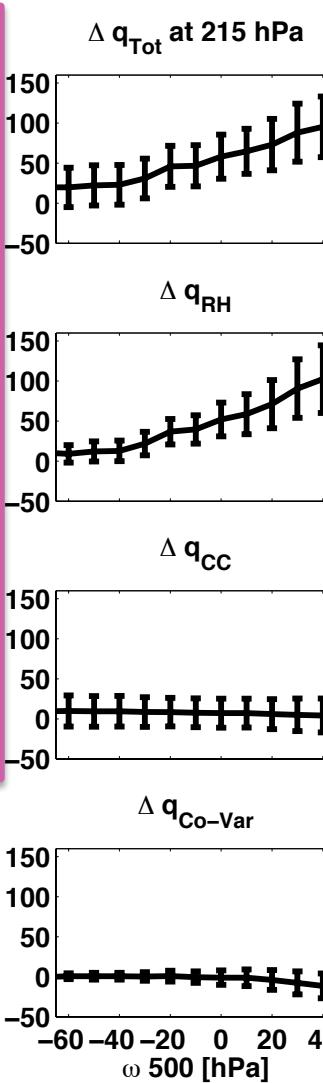
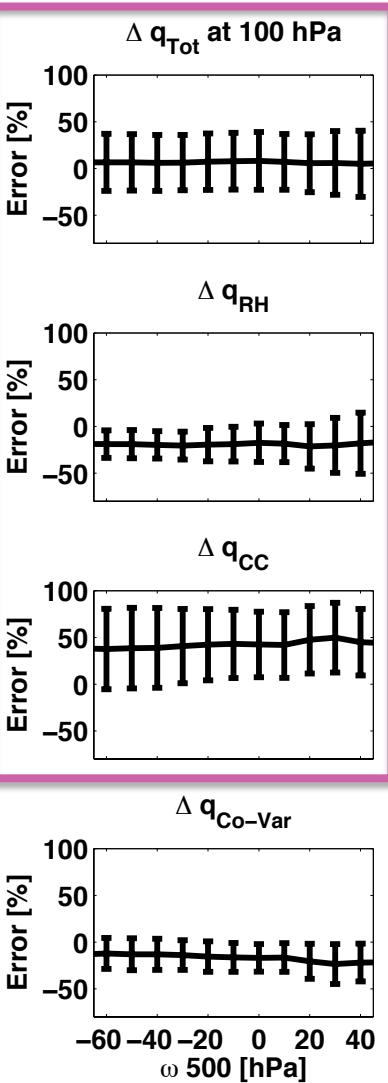
Errors in Climatological Mean: Fractional UTWV Error Decomposition

LS

UT

MT

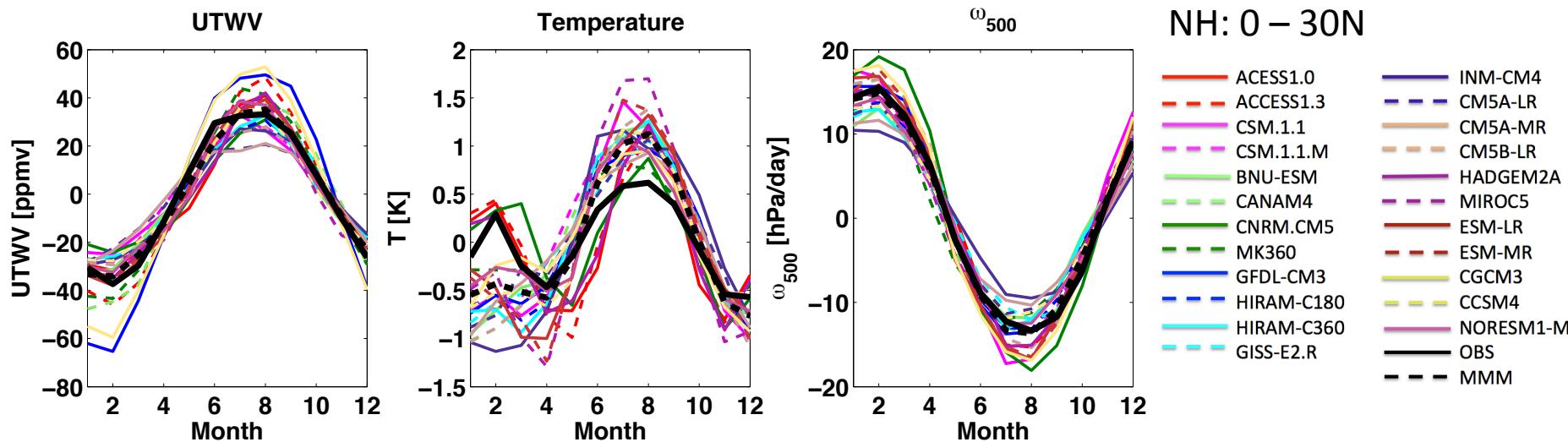
LT



Each component is sorted by observed climatological ω_{500} with a bin interval of 10 hPa/day.

- ❖ Dynamics play a dominant role in the water vapor errors, except LS.
- ❖ Thermodynamics and dynamics contribute comparably to the water vapor errors at LS.

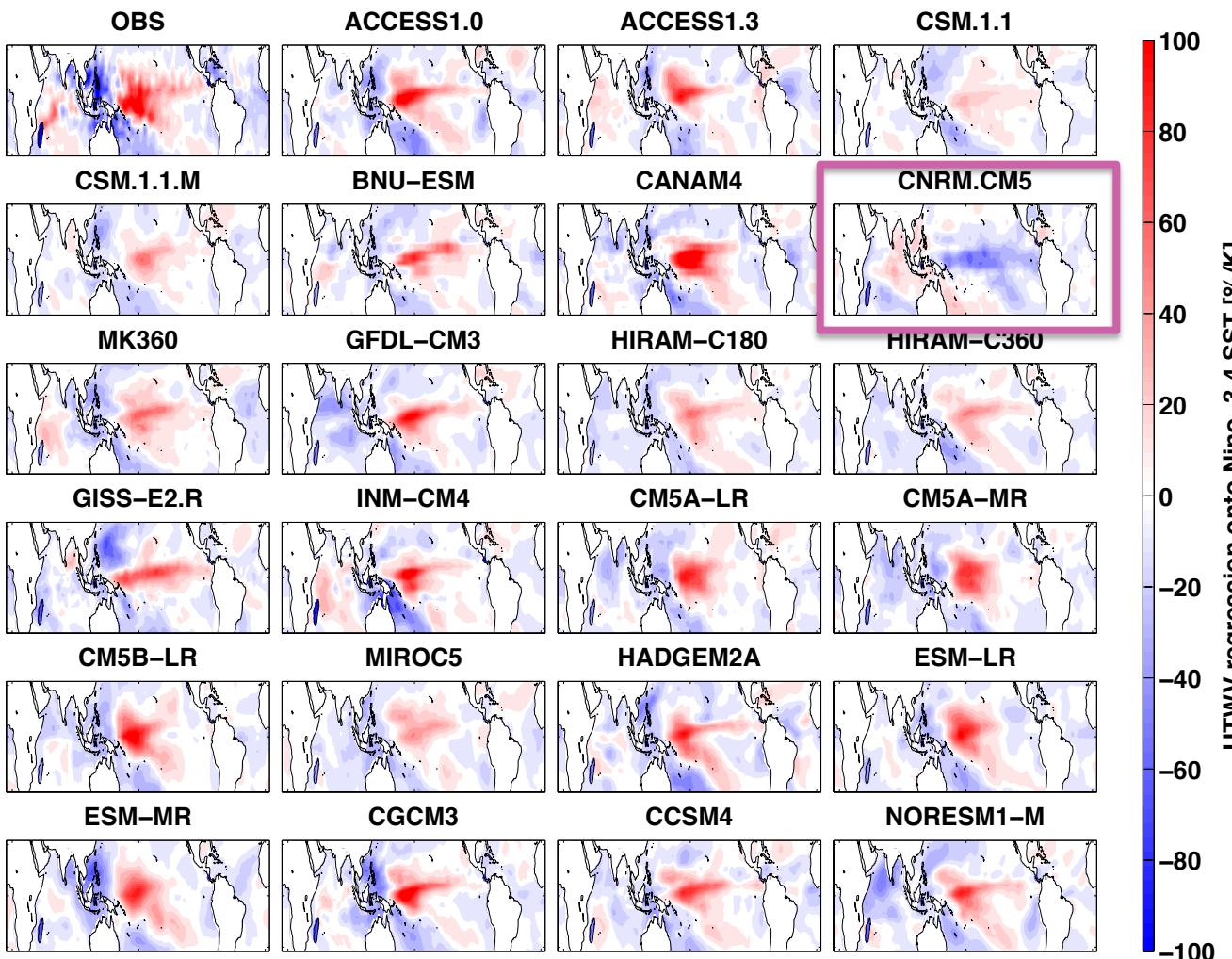
Errors in Seasonal Cycle: Patterns of Seasonal Variation



- ❖ The seasonal variations are the monthly anomalies after the annual mean is removed.
- ❖ The MMM UTWV agrees well with the observed UTWV in phase and in amplitude, but the inter-model spreads in amplitude are not negligible.
- ❖ T has large inter-model spread, while ω_{500} has small spread from the figure.
- ❖ Correlations between UTWV and ω_{500} (-0.95~ -1.00) are higher than that between UTWV and T (0.4~0.98).

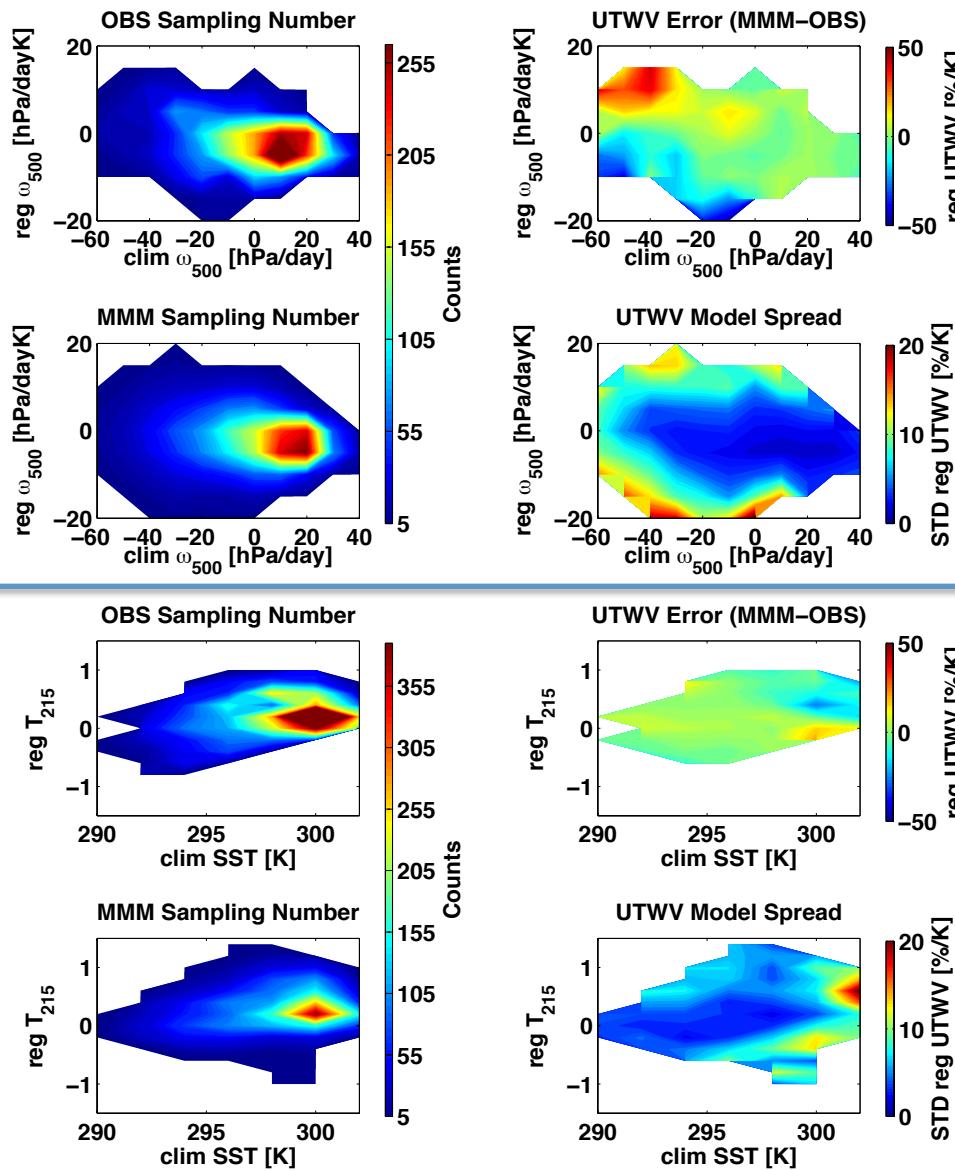
Errors in Interannual Variability: Regression of UTWV onto Niño-3.4 SST

To test how observed and simulated UTWV respond to ENSO, linear regression of UTWV monthly anomalies onto the Niño-3.4 SST (5°S – 5°N and 190° – 240°E) are examined.



- ❖ Models (except CNRM) generally capture the UTWV response to ENSO (positive regressions over central and eastern Pacific and negative regressions over western Pacific), but **amplitude differences are outstanding.**

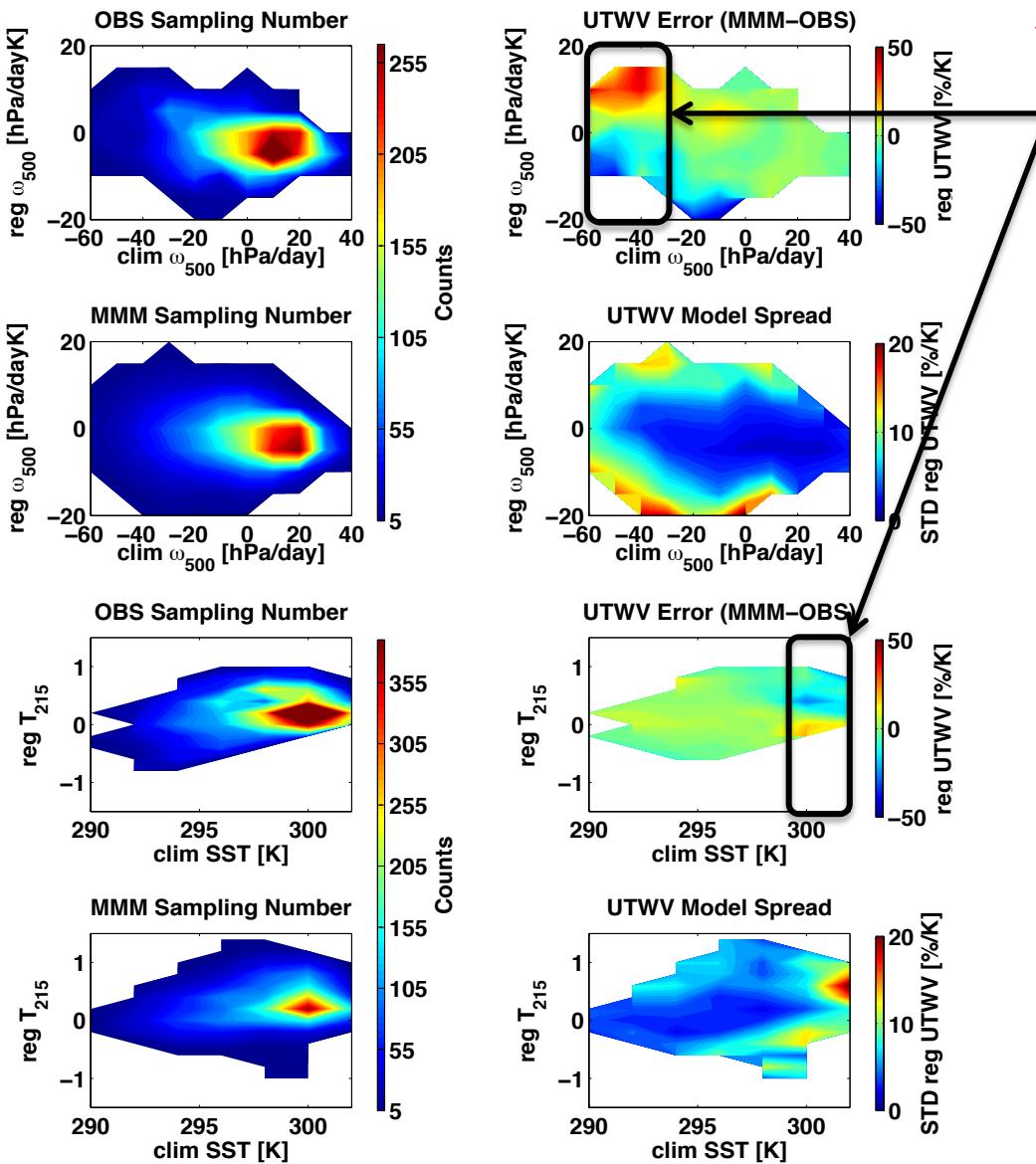
Errors in Interannual Variability: Regression of UTWV onto Niño-3.4 SST sorted by T



UTWV errors response to ENSO sorted by both climatological ω_{500} (x-axis) and ω_{500} anomalies response to ENSO (Y-axis).

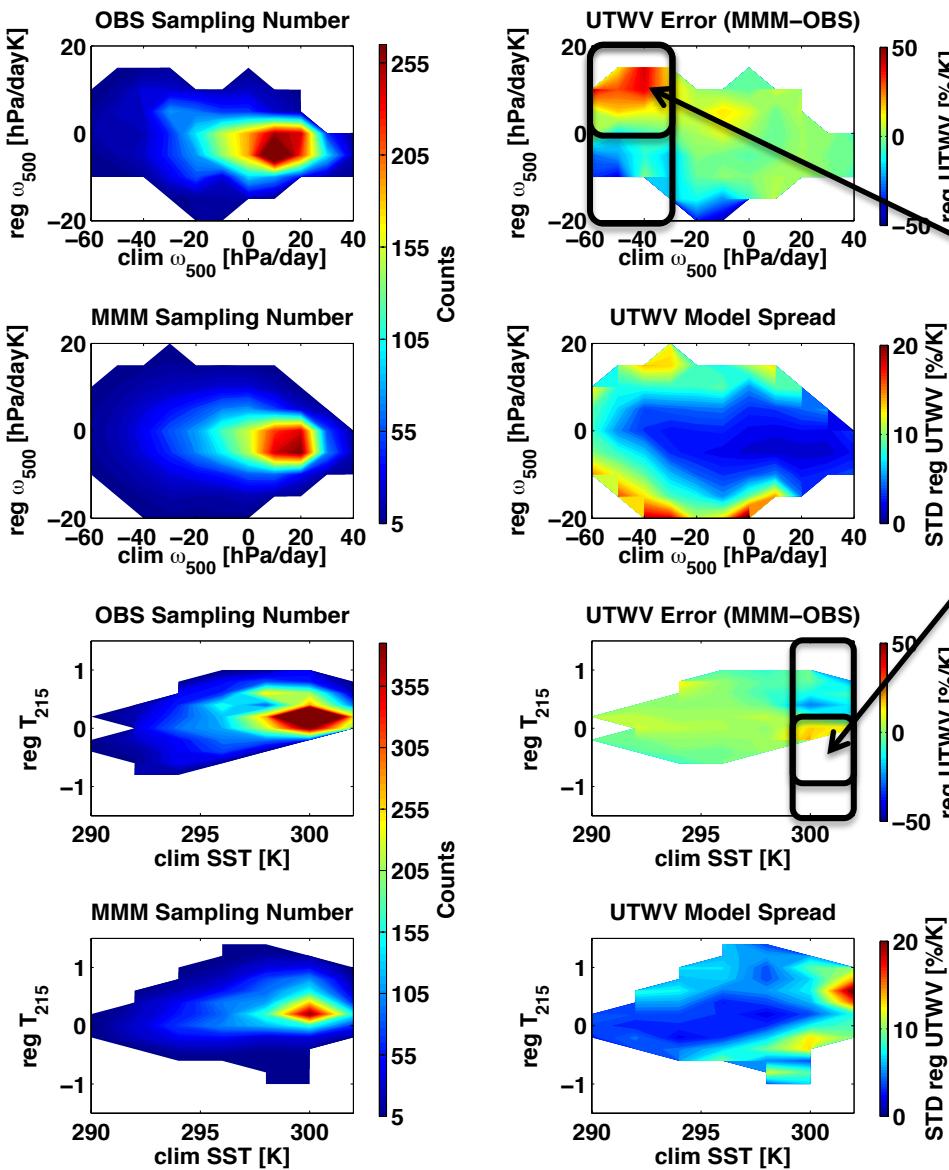
UTWV errors response to ENSO sorted by both climatological SST (x-axis) and T_{215} anomalies response to ENSO (Y-axis).

Errors in Interannual Variability: Regression of UTWV onto Niño-3.4 SST sorted by T



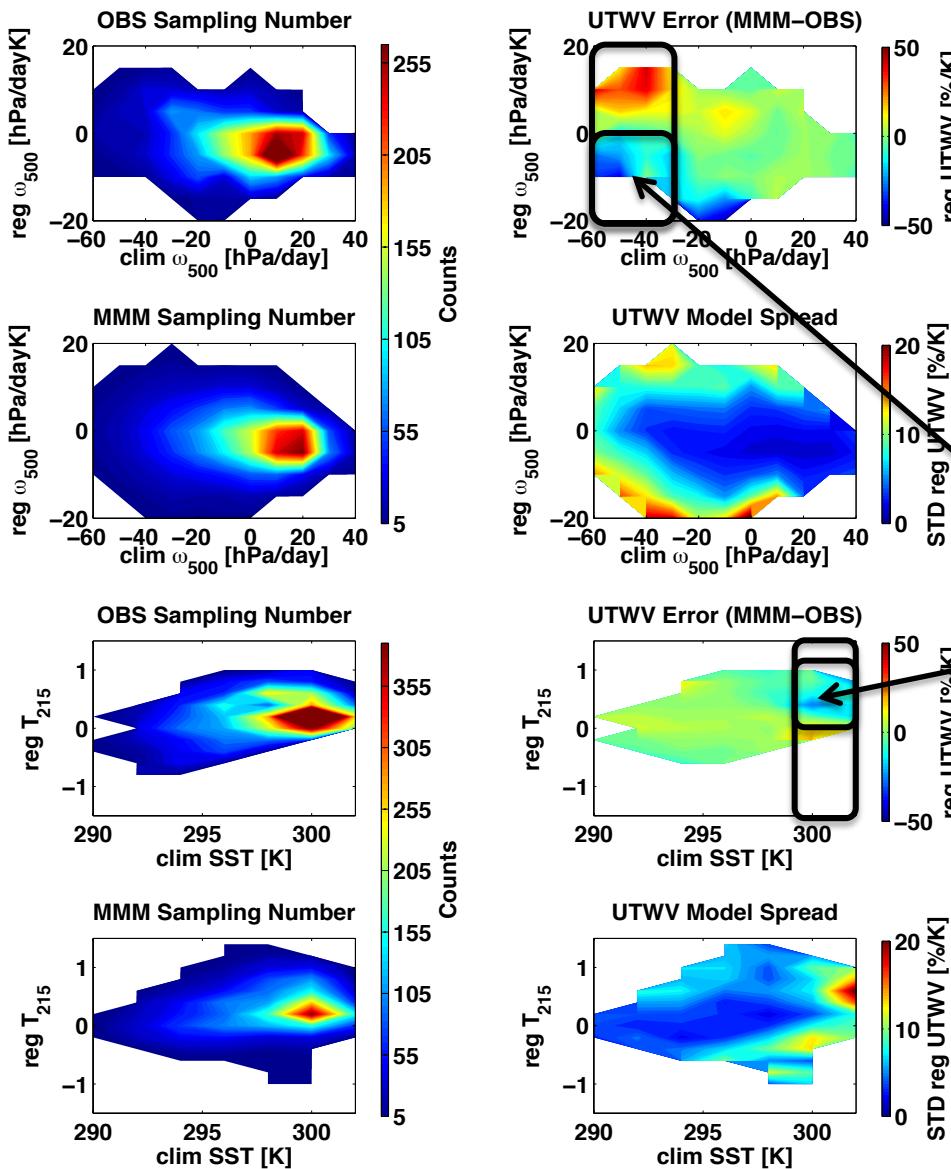
- ❖ UTWV errors are abundant over the climatologically convective regions ($SST > 300K$ or $\omega_{500} < -30$ hPa/day), where deep convection predominates.

Errors in Interannual Variability: Regression of UTWV onto Niño-3.4 SST sorted by T



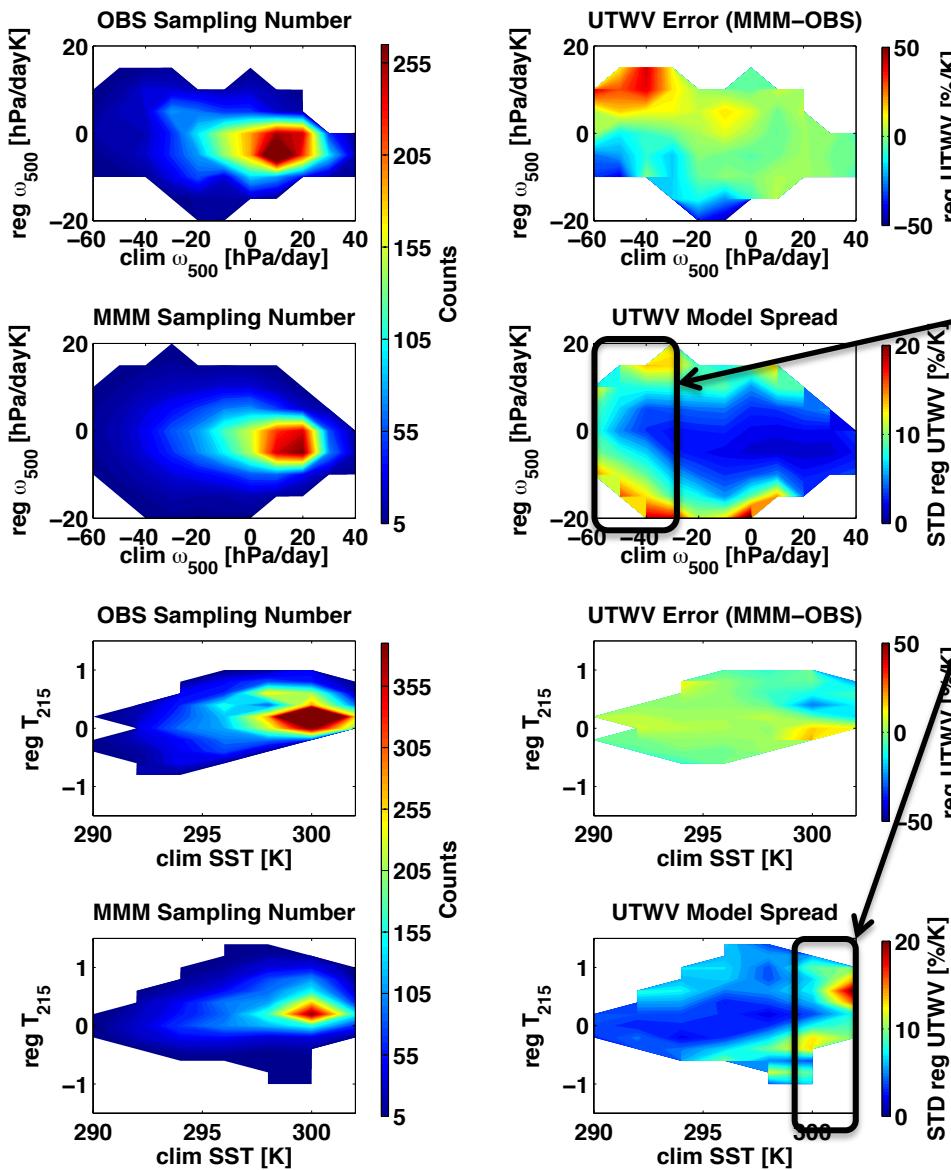
- ❖ UTWV errors are abundant over the climatologically convective regions ($SST > 300K$ or $\omega_{500} < -30$ hPa/day), where deep convection predominates.
- ❖ Simulated UT is **wetter** than observed in regions that experienced anomalous descent and cooling.

Errors in Interannual Variability: Regression of UTWV onto Niño-3.4 SST sorted by T



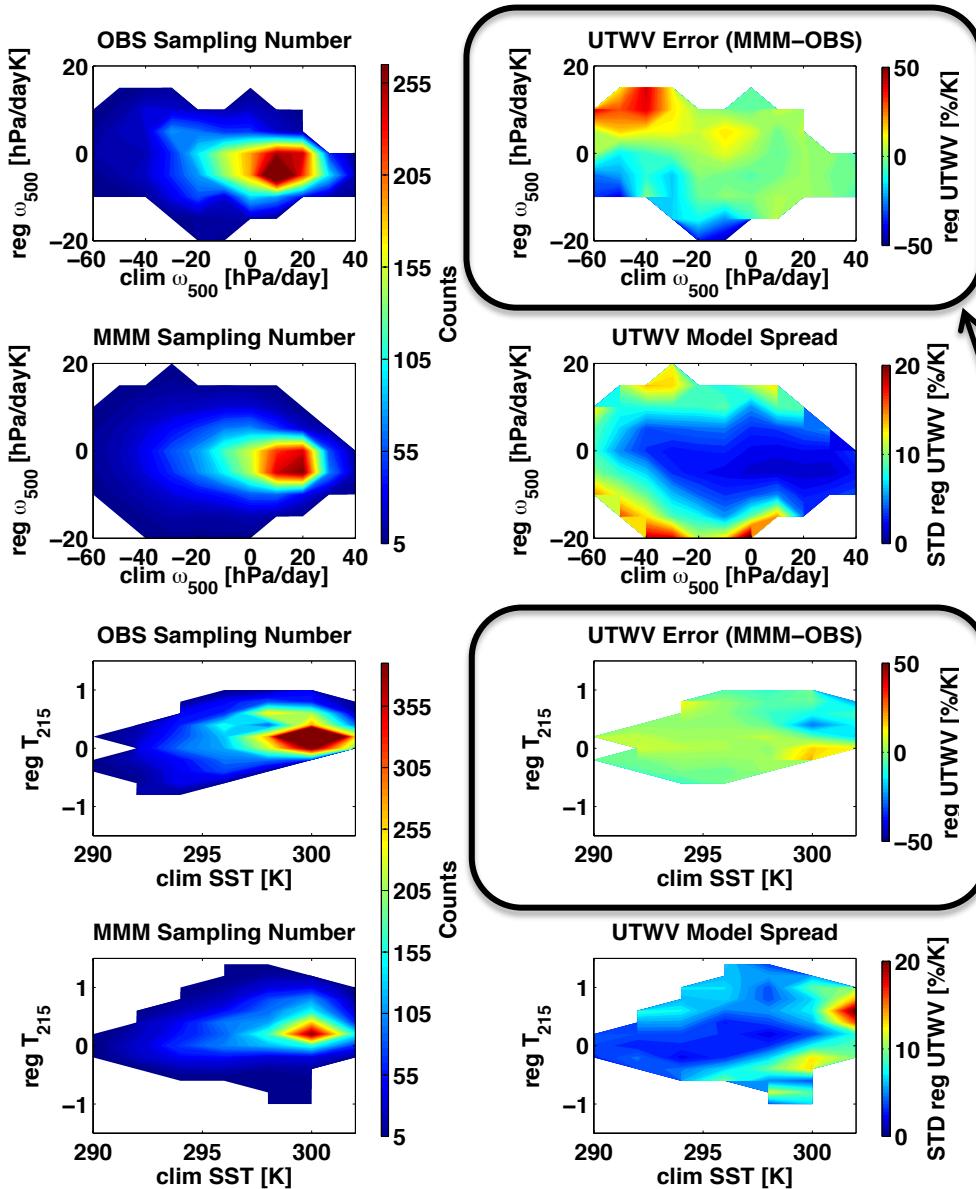
- ❖ UTWV errors are abundant over the climatologically convective regions ($SST > 300K$ or $\omega_{500} < -30$ hPa/day), where deep convection predominates.
 - ❖ Simulated UT is **wetter** than observed in regions that experienced anomalous descent and cooling.
 - ❖ Simulated UT is **drier** than observed in regions that experienced anomalous ascent and warming.

Errors in Interannual Variability: Regression of UTWV onto Niño-3.4 SST sorted by T



❖ Model spreads are large over the climatologically convective regions ($\text{SST} > 300\text{K}$ or $\omega_{500} < -30 \text{ hPa/day}$), where deep convection predominates.

Errors in Interannual Variability: Regression of UTWV onto Niño-3.4 SST sorted by T



- ❖ Model spreads are large over the climatologically convective regions ($SST > 300K$ or $\omega_{500} < -30$ hPa/day), where deep convection predominates.
- ❖ The amplitude of model errors are generally larger in the dynamic scales than that in the thermodynamic scales.

Dynamics play a dominant role in the amplitude errors.

Summary of Results

This study untangles the sources of simulated UTWV errors by analyzing the relative contributions to UTWV errors by dynamics (ω) and thermodynamics (T).

In general, **large-scale dynamics are prevailing for controlling UTWV errors in climatological mean, seasonal cycle, and interannual variability.** Thus, **accurate representation of dynamics (large-scale circulation and convection) is critically important** for simulations of UTWV and its climate feedback.

Summary of Results

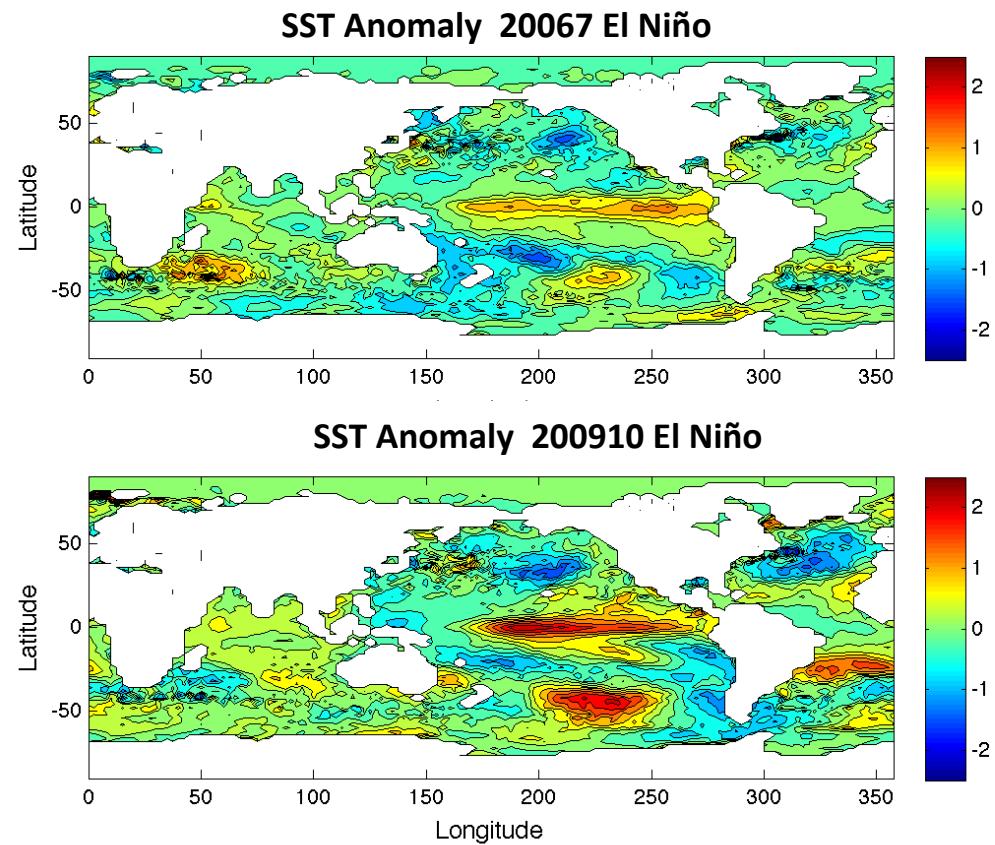
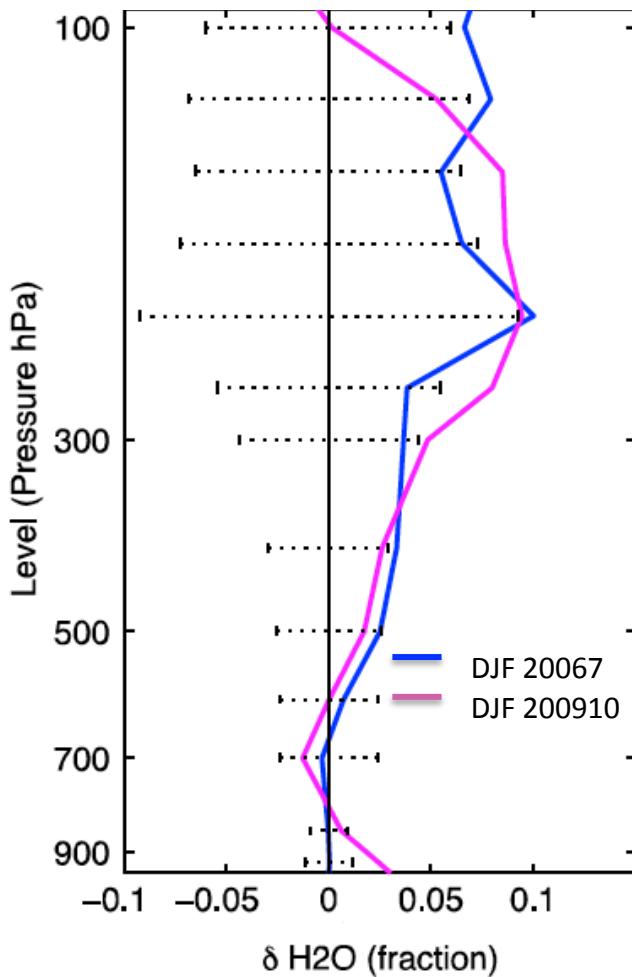
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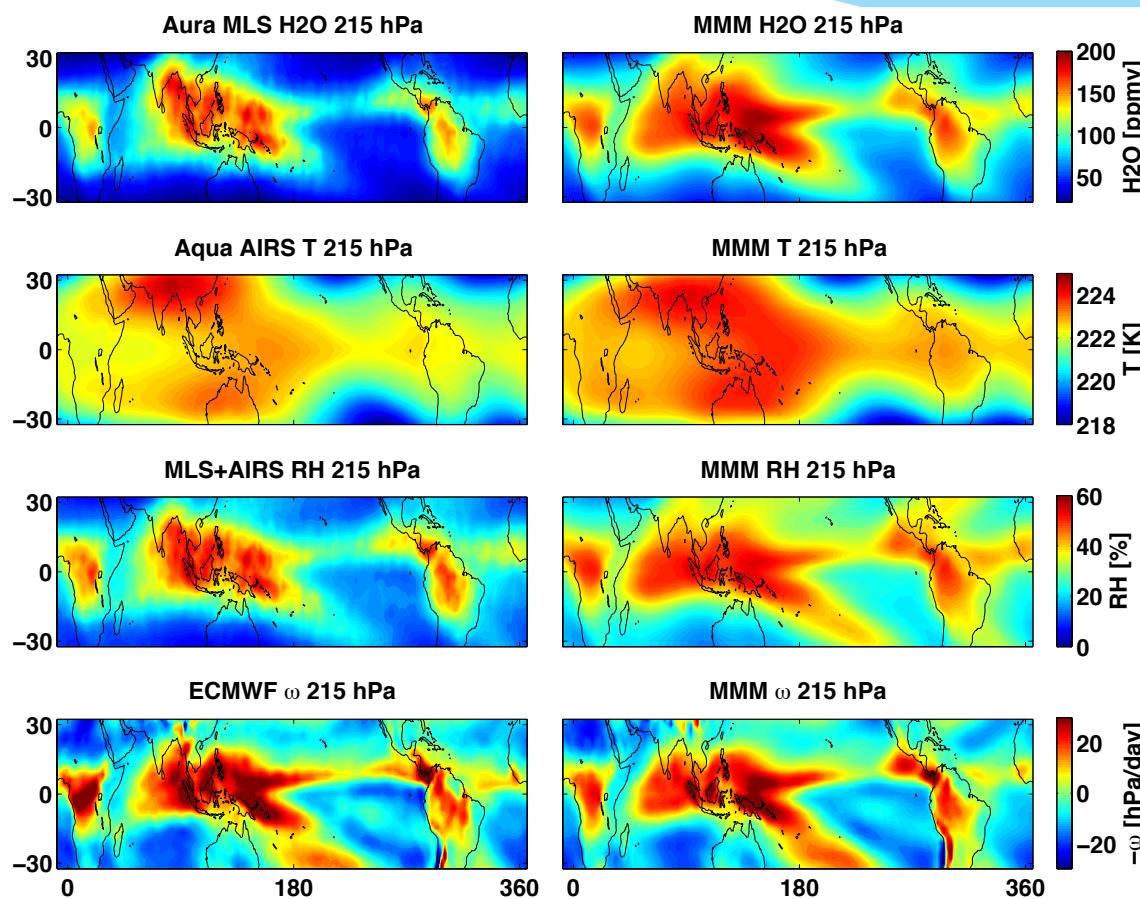
Background: Why UTWV is important?

- ❖ Water vapor is the primary contributor of atmospheric greenhouse effect, which is also the dominant positive feedback in our climate system.



- ❖ “upper tropospheric amplification” of water vapor response to the SST warming (Takahashi et al., 2013).

Introduction: Maps of satellite observation and MMM



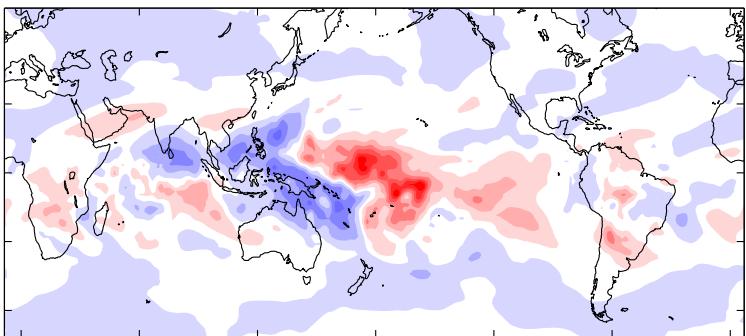
$$RH = q/q^*(T)$$

where RH is relative humidity, q is specific humidity, and $q^*(T)$ is saturation specific humidity, respectively.

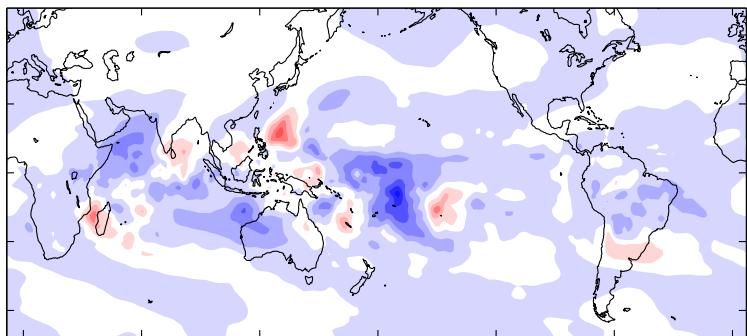
- ❖ Multi-model mean (MMM) captures the general patterns of observations, but the amplitude differences are outstanding .
- ❖ Patterns between UTWV, RH and ω are similar, but T exhibits a different pattern.

DJF Anomalies

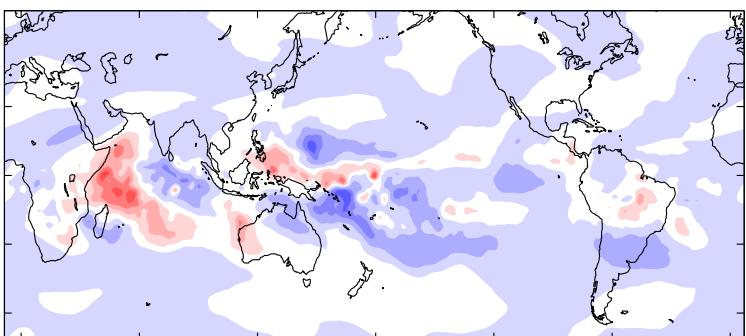
CNRM–CM5 2004–2005



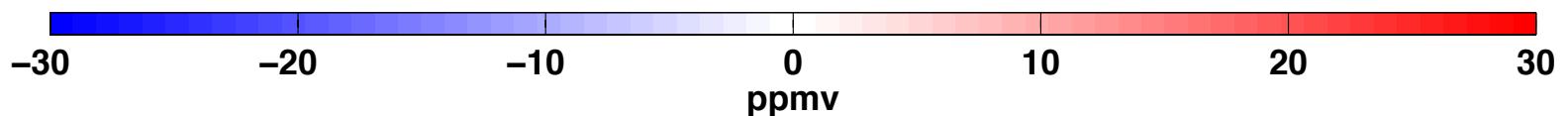
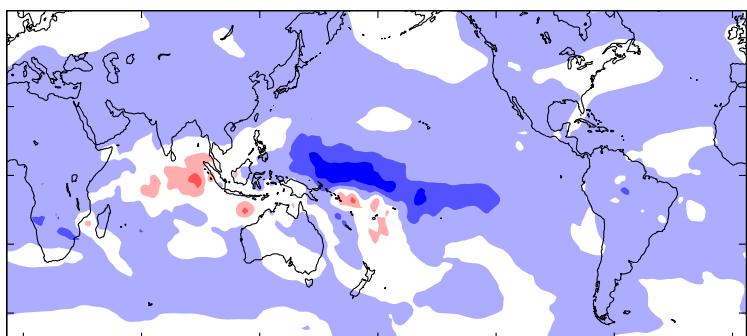
2005–2006



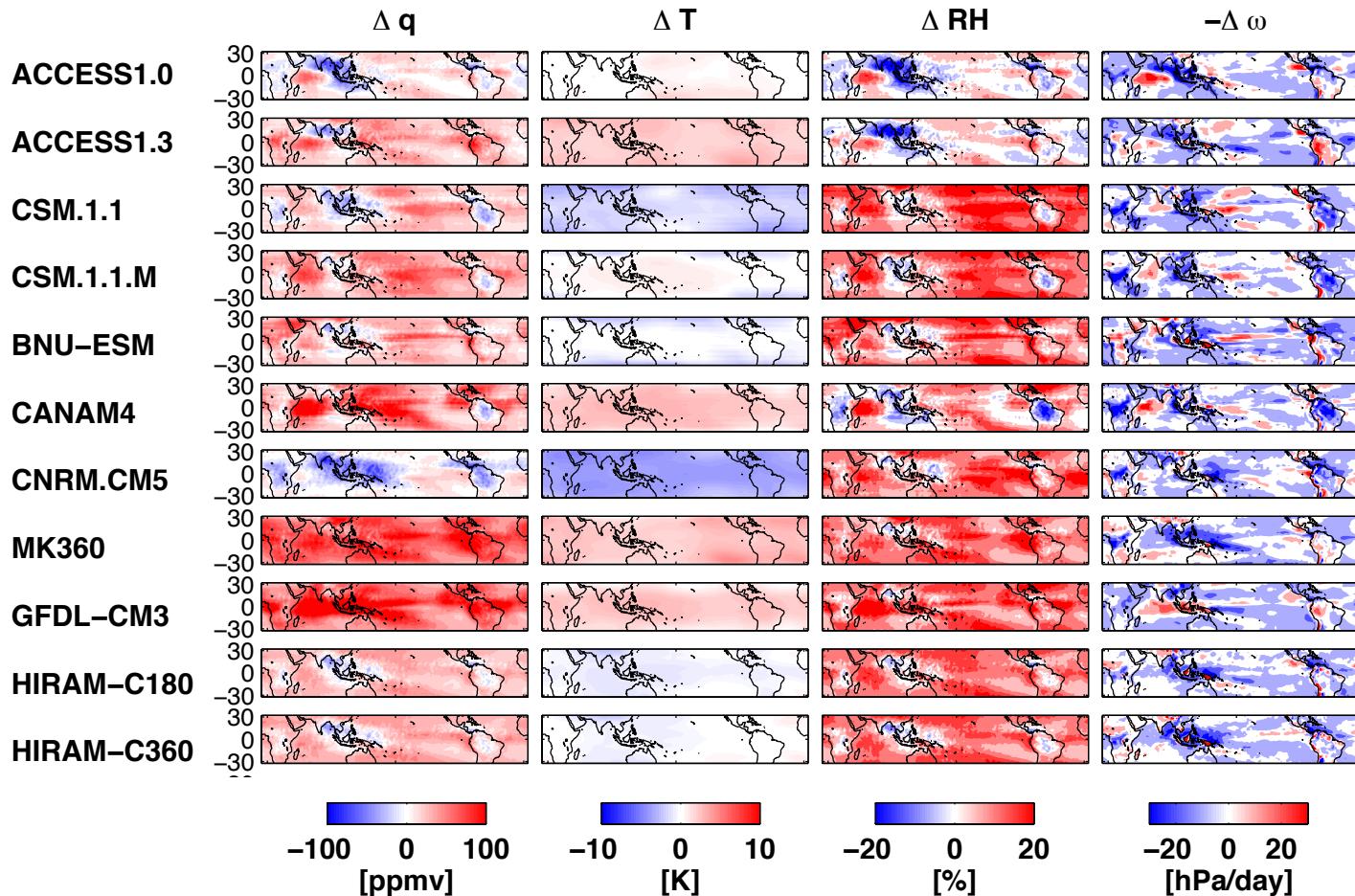
2006–2007



2007–2008



Errors in Climatological Mean: Comparison of Errors in Different Variables



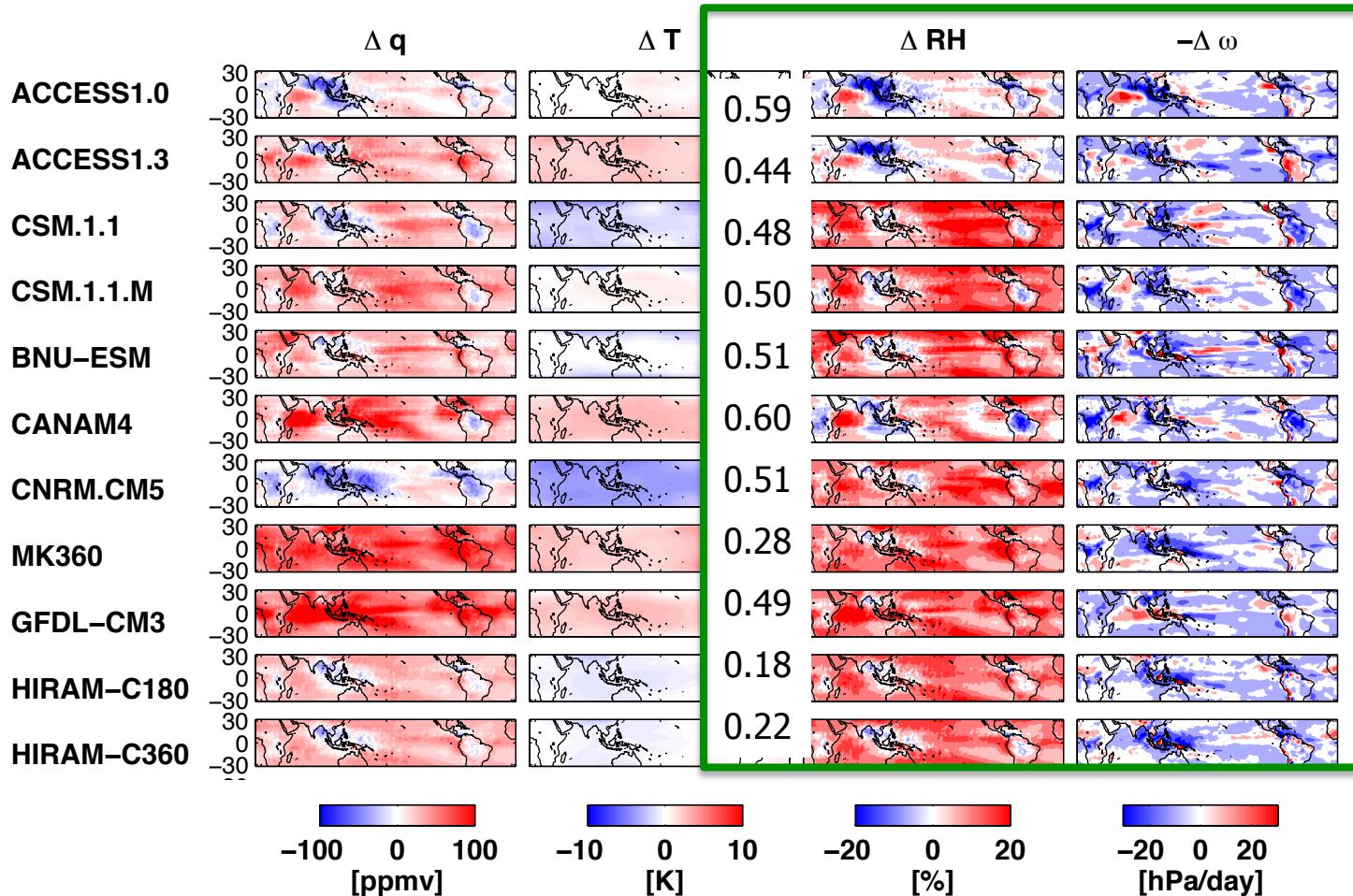
We define model errors as:

$$\Delta(*) = (*)_m - (*)_o$$

and Δ terms are normalized by their standard deviations.

- ❖ Models generally have wet biases in the UT.
- ❖ Patterns of UTWV errors are generally more similar to those of ω_{215} errors than to those of T errors.

Errors in Climatological Mean: Comparison of Errors in Different Variables



We define model errors as:

$$\Delta(*) = (*)_m - (*)_o$$

and Δ terms are normalized by their standard deviations.

- ❖ The patterns of RH biases are highly correlated with ω_{215} biases.

Background: Why UTWV is important?

Tett et al., 1996, & Held and Soden, 2000

- ❖ Water vapor is one of the primary contributors to the atmospheric greenhouse effect, and upper UTWV plays a key role in amplifying global warming.

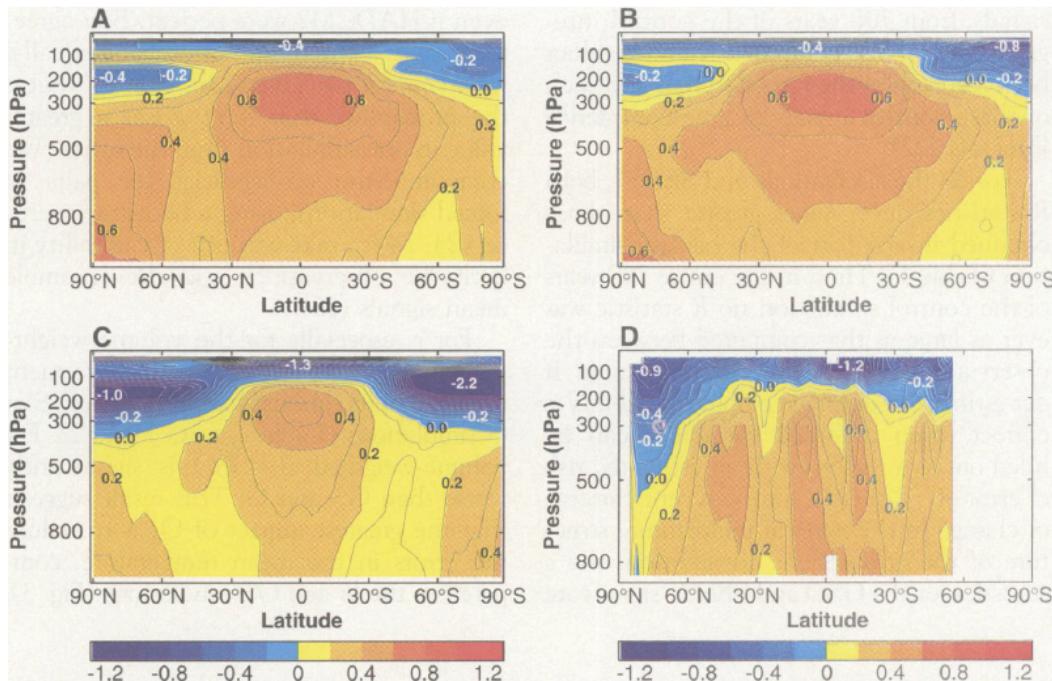


Fig. 2. Simulated and observed zonal mean temperature changes. **(A)** G signal; **(B)** GS signal; **(C)** GSO signal; and **(D)** observations. All signals are shown as a function of latitude and height and use a contour interval of 0.1 K. All signals are defined to be the difference between the decadal mean from 1986 through 1995 and the 20-year mean from 1961 through 1980.

- ❖ Difference between T(1995~1986) and T(1980~1961).
- ❖ Climate models predict that warming in the tropics is larger in the UT than in the LT.
- ❖ It because the moist adiabatic lapse rate decrease with increasing temperature (Held and Soden, 2000).